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Electrokinetically enhanced pipe flow of coal-water suspensions using a non-intrusive helical anode-cathode geometry.

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Abstract

It has been experimentally demonstrated that the application of electrokinetic techniques in the continuous flow of coal-water suspensions within a helical anode-cathode pipe geometry effectively causes a significant reduction in the wall shear stress. This reduction in the frictional force at the cathodic pipe wall surface is attributed to a decrease in the concentration of coal particles in this flow region caused by the migration of negatively charged coal particles towards the anodic surface(s). The disadvantage of flow-intrusive geometries is the reduction in effective flow area as well as an increase in frictional surface area caused by the placement of the anode(s) within the flow region. Experimental data is presented for a non-intrusive helical anode-cathode geometry embedded in the pipe wall which shows that a reduction in pumping energy of approximately an order of magnitude is possible. A sample of sub-bituminous black coal fines having a mean particle size of approximately 17 microns was used to prepare coal-water suspensions with a solids concentration of 50%(w/w). The practical and economic implications of this work relate to an enhanced method of long distance transportation of slurries in pipes as well as an alternative technique for continuously separating solid-liquid suspensions.

Introduction

The production of fine coal particle wastes and by-products has increased as a result of the continuous mining methods and beneficiation processes relevant to the coal industry. An inherent challenge with the production of fines is a relatively high moisture content which introduces technical and economical difficulties in the handling, disposal, dewatering and reusability of coal fines. Tailings dams are a common method of disposal and storage of coal wastes produced by coal preparation plants operating in Australia and throughout the world.

The oil and energy crisis that occurred in the 1970's generated further interest in coal-slurry fuel technology and the economics of alternative fuels, renewable energy sources and coal slurry transport systems. Contemporary ethical issues such as sustainable resource development [4] has directed political and economic pressure on the mining industry and government bodies to improve the utilisation of current resource levels and to limit any detrimental effects on the environment. Australia's prolific arid regions also provide the major industrial mining companies with economic and environmental incentives to close plant water circuits. An alternative water supply such as municipal sewage sludge (>95% water) is used in the United States to produce a coal-sludge fuel slurry [2].

In the presence of a DC electric field ionic species and solid particles possessing a net electrostatic charge relative to the aqueous phase in a solid-liquid suspension, will migrate towards the oppositely charged electrode. As opposed to hydraulic flow this externally induced flow is driven by electrokinetic forces which are primarily a surface phenomenon and are essentially independent of pore size and its distribution. Electrophoretic experimentation was pioneered by Reuss [21] in the early 1800's with his description of the migration of clay particles in the presence of an electric field. Further work by Hittorf [7] on a system of silver electrodes immersed in a solution of silver nitrate showed that changes in the anode-cathode ion concentration profile occurred when an electric field is applied. Although Kohlrausch [13] determined the electrokinetically induced velocities of certain ions, and Arrhenius [1] provided additional experimental and quantitative data, it was not until the work of Picton and Linder [19,20] in the 1890's that electrophoretic migration was proposed as a viable method of solid-liquid separation.

Chemical, biological and natural sedimentation methods used in the dewatering of concentrated suspensions of fine particles are generally inefficient and economically unfavourable. The use of electrokinetic techniques for the purpose of dewatering slurries has been applied to mineral slurries, [14,15] mill tailings, slimes and coal wastes [17,33,34]. Previous experimental work [16,18] carried out in a continuous 'in-pipe' electrodewatering system shows that a significant reduction in the wall shear stress as well as partial dewatering of coal-water suspensions occurs. In this process a 3.0 mm tube acting as the anode is centrally aligned in a 12.62 mm pipe which is the system cathode. Isaacs and Speed [10] proposed the use of a fluid film of lower viscosity to reduce the pumping energy requirements of a highly viscous crude oil flowing in pipes. Capsule pipeline transportation was developed by Hodgson and Charles [8] in 1963 as an alternative method of reducing pressure gradients when moving solids in a pipeline. Other novel techniques of hydraulic transport of solids include the use of a fibre suspension to support a dense phase core [6] and the injection of viscosity modifiers at the wall of a slurry pipeline [9]. The scope of this study is to investigate the possibility of reducing the wall shear stress of concentrated slurries flowing in pipes with an electrode arrangement located within the pipe wall itself rather than within the flow field.

Experimental Method

Rheological data was generated using a tube rheometer set up where pressure gradients and flow rates were measured and recorded on a computer data logging system. In order to calibrate the pressure transmitter and load cell as well as to test the data acquisition software a standard Newtonian fluid (98% glycerol solution at 20˚C) was initially run through the system. A small increase in the expected pressure differential (< 2.5%) was measured and attributed to the effect of any irregularities on the inner surface of the pipe caused by the presence of the anodes and insulating material.

The solids concentration of the suspensions tested in this experimental trial was determined using a standard constant weight difference in a drying oven. A typical solids concentration of approximately 50% w/w was used and the mixture was mixed using a mechanical agitator in the slurry vessel before each experimental run. The suspension temperature was adjusted and monitored before and after each run (20˚C ± 1.2˚C). Figure 1 outlines the experimental set-up used to generate the rheological pipe flow data under electric field conditions. A section of pipe was inserted prior to a 1 metre helical pipe test length so as to ensure fully developed flow conditions. The pitch of the helical pipe section was set at 4 helical turns per metre.

The experimental approach involved varying the electric field strength for a particular initial flow rate which was controlled by an air pressure regulator on the slurry vessel. A variable DC power supply is connected to the tube rheometer which is electrically insulated from the other components of the experimental apparatus.

An Australian low rank bituminous black coal is used in all experiments. Coal particle sizes above 75µm were removed by screening which produced a material of coal fines having a d_{50} of 17.2µm. Due to the particle size distribution of the coal fines, the high solids concentration and the short time scale of the experimental runs any possible settling or stratification effects within the pipe where considered to be negligible.

Concentrated solid-liquid suspensions commonly exhibit slip effects at the flow contact surfaces. This phenomenon is present both in pipe flow and the various measuring equipment used in rheological analysis. In order to determine the extent of slip at the flow boundaries in a tube rheometer, flow data should be generated for different diameter values. To neglect the effect of slip, the flow curves should be independent of tube diameter. In this study the correction for slip effects was not carried out due to the availability of only one helical pipe assembly.

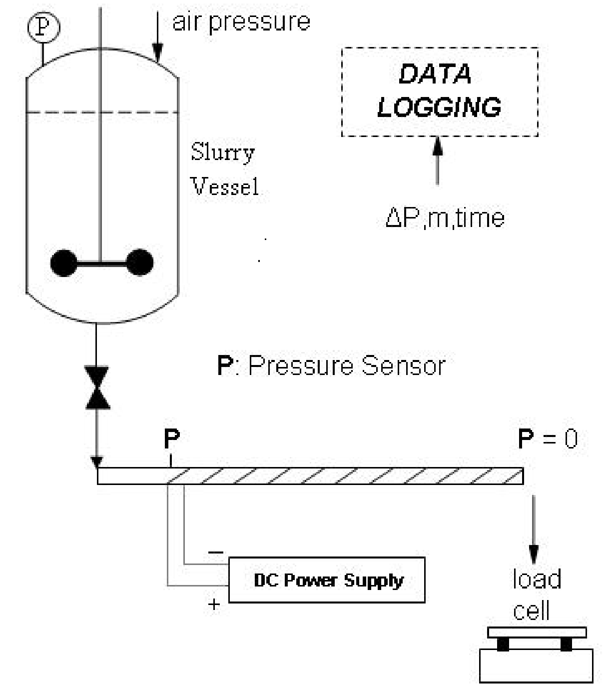

Figure 1. Experimental set-up used to generate rheological data.

Figure 2 describes the helical pipe section [22,26] showing the anode-cathode arrangement, the electrically insulating outer pipe casing and the narrow plastic strips inserted to ensure that the electrodes do not short the electrical circuit. Polished copper metal was used as the material of construction for the electrodes so as to provide good electrical conductivity and practicality. At the end of the experimental program the inner surface of the helical pipe was inspected and there was no physical evidence of corrosion or pitting that may have arisen due to the application of the electric fields.

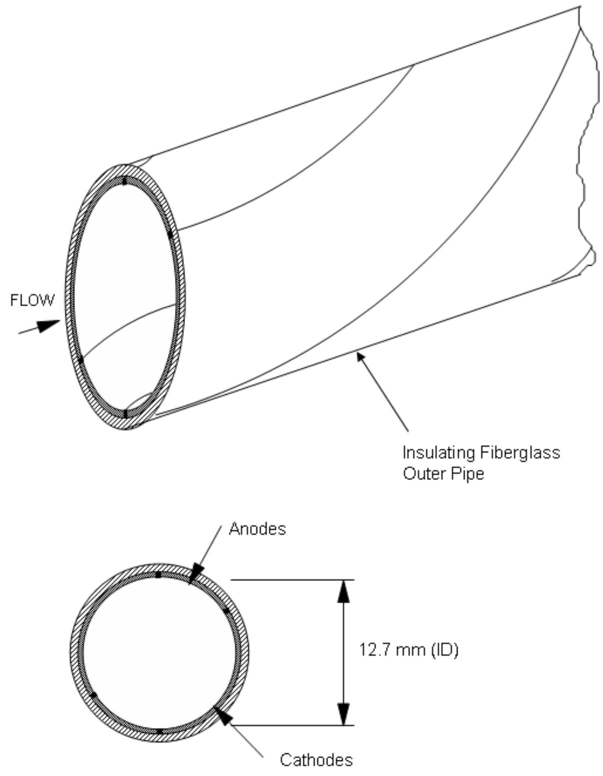

Figure 2. Anode-cathode arrangement in the helical pipe [22,26].

Discussion of Results

Rheological and Pumping Energy Data

The typical effect of electric field intensity and the initial mean axial velocity on the flow behaviour is shown in Figure 3. At a constant slurry vessel pressure a reduction in the shear stress or pressure gradient and a simultaneous increase in mean flow rate or shear rate is measured when the electric field is applied. This effect is enhanced as the electric field strength in increased and at low flow rates where the initial residence time in the helical pipe section is maximised.

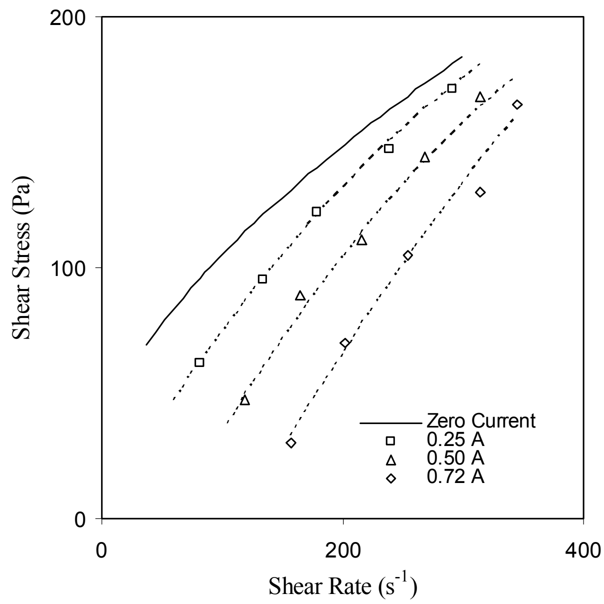

Figure 3. The effect of electric field intensity on a coal-water suspension (solids volume fraction 0.42 v/v).

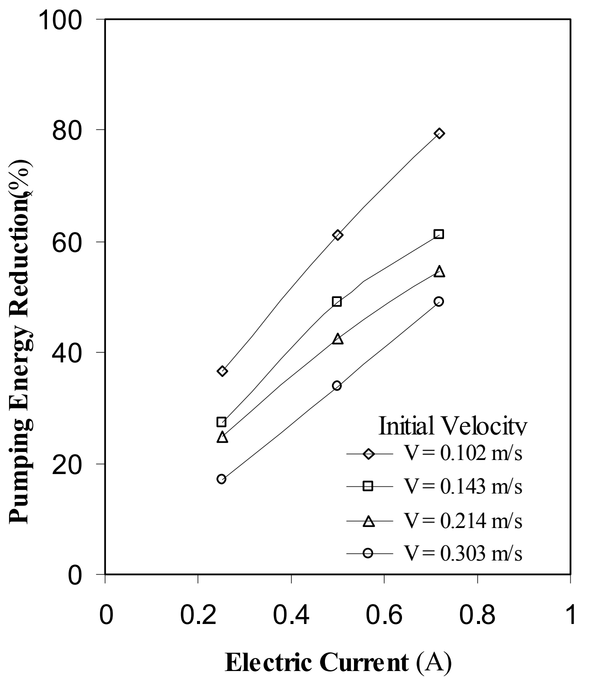

Figure 4. The effect of applied electric current and initial velocity on the reduction in pumping energy.

Figure 4 shows the effect of applying an electric current on the pumping energy reduction at various initial flow velocities. The magnitude of the pumping energy across the test pipe length is simply determined by the product of the pressure gradient and the volumetric flow rate. The pumping energy reduction is based on the change in pumping energy from the zero electric field conditions to the enhanced flow conditions at a specific flow rate. A pumping energy reduction of 79% is measured at a high electric current and low initial velocity. As the electric current is lowered the flow enhancement is also reduced.

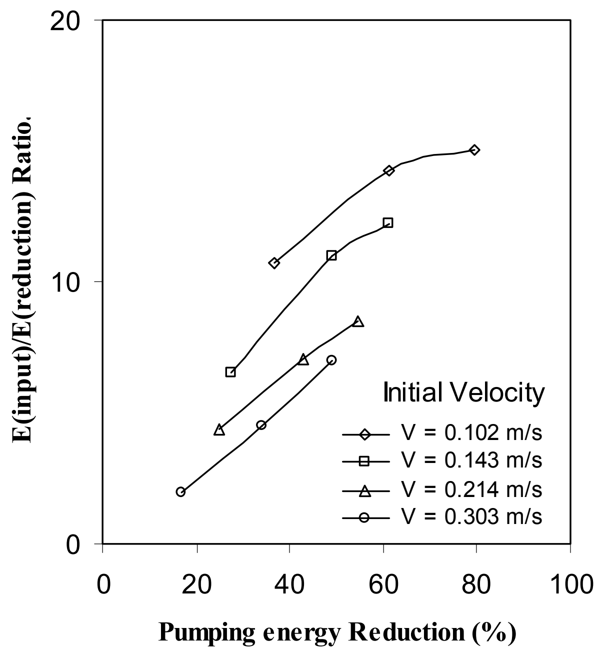

Figure 5. The variation in the ratio of the electrical energy input and the absolute pumping energy reduction at various initial velocities.

The electrical energy input compared to the actual reduction in pumping energy is an important factor in determining the feasibility and economic viability of using electric fields to enhance the flow of slurries in pipes. Figure 5 shows the variation in this energy ratio as the pumping energy reduction is increased at various initial flow conditions. For the small pipe diameter used in this experimental study, the electrical energy input can be as high as 15 times the actual pumping energy gains achieved by the flow enhancement. For this pipe diameter it would be economically unfavourable to apply the electric field along the entire length of a slurry pipeline system.

Further experimental work is required using pipe systems with greater diameters in order to determine the scale-up efficiency of this flow enhancement technique. A comparison of experimental results for various flow intrusive anode-cathode systems highlights the dependence of flow enhancement on the initial velocity and the electric field intensity at the flow contact surfaces [23,31]. Studies on other concentric and eccentric anode-cathode systems reveal that the frictional losses associated with the surface area of the anode become important at high initial velocities [23,26,29-31].

The economic feasibility of a coal-water slurry pipeline system using an intermittently spaced anode-cathode arrangement is related to the stability of the local concentration of solids at the pipe wall and its degradation with time when the electric field is switched off. Previous experimental work has confirmed the stability of flow conditions in a 12.62mm [16] and a 21.4mm [27] pipe system with a centrally aligned anode. In order to minimise the construction costs and optimise the energy requirements of electrokinetically enhanced pipe flow, the intermittent spacing of the flow enhancement units along the pipeline needs to be maximised. Further study into the stability of flow and concentration profiles within the pipe system is required.

Fluid flow modelling and experimental data relating to a concentric annular anode-cathode pipe geometry [23-25] shows that a relatively thin film of low solids concentration at the cathode can produce significant reductions in pumping energy. The modified flow conditions resulting from the application of an electric field in this concentric annular system generates a dense phase core region. At high electric field strengths the shear rate distribution within this dense phase central core approaches zero and its flow behaviour can be approximated by a plug flow regime. The ‘maximum packing’ volume fraction will provide an upper physical limit to the electrokinetically modified solids concentration profile. Similarly, a zero solids concentration limit is applicable to the lubricating film region. In reality there will be a non-uniform distribution of coal particle migration velocities which would produce a continuously changing solids concentration profile unlike a simple two-layer fluid flow model.

Microscopic Study and Particle Interactions

The simple case of the motion of a freely-suspended, uniformly charged sphere under an arbitrary applied electric field is examined. The generalised Smoluchowski equation [32] is applicable in determining the ‘unhindered’ electrophoretic velocity of a coal particle. Although the application of the Smoluchowski relationship to a concentric annular geometry enables the prediction of the velocity of a charged particle subjected to an electrical field, the effects of inter-particle interactions at higher volume fractions also need to be considered. This problem of correcting the unhindered Smoluchowski particle velocity for concentration effects can be initially examined with respect to two spheres of arbitrary size and orientation that are being influenced by an electrical field [23]. The interactions of interest in this system are electrostatic and hydrodynamic in nature and do not include any boundary wall effects. An approximation can be made of the hindered

electrophoretic particle velocity by determining these interaction coefficients.
The effect on fluid properties such as apparent viscosity when an electric field is applied was examined by Duff [5] almost a century ago and then by Winslow [35] in 1949 and is today commonly referred to as the electrorheological effect. In disperse systems Klass and Martinek [12] suggested that the polarisation of the particle double layer is the primary mechanism responsible for the observed increase in the apparent viscosity of fluids and solid-liquid suspensions that exhibit electrorheological behaviour (see Figure 6). The close range dipole interactions associated with concentrated coal-water suspensions and the presence of a conducting polar liquid phase are important factors which cause deviation from this disperse system approximation.

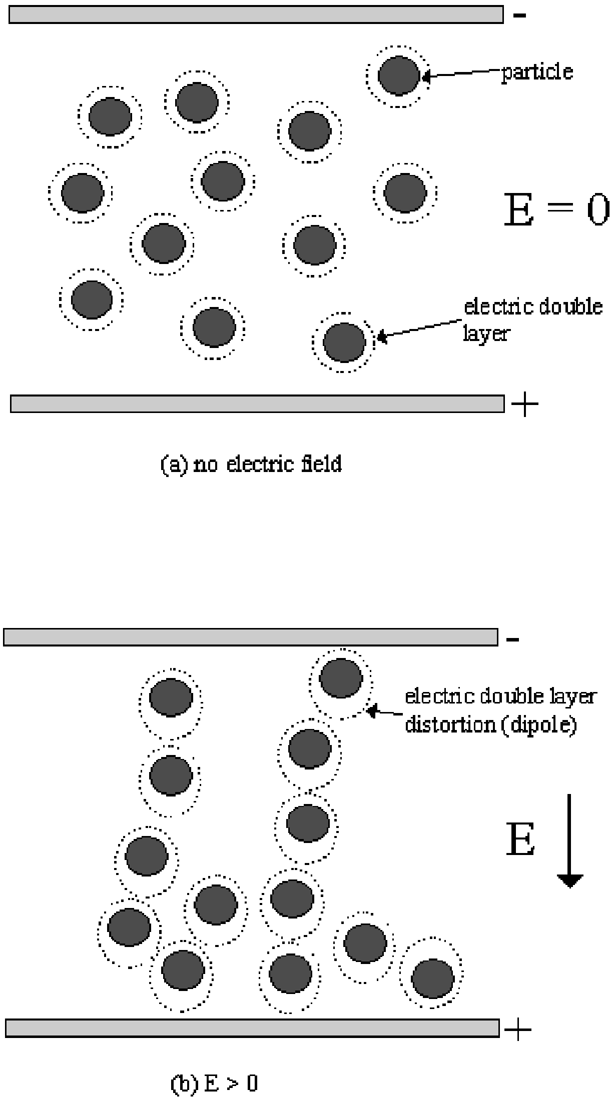

Figure 6. Schematic diagram showing the formation, distortion and interaction of the electric double layer when an electric field is applied in a dilute solid-liquid suspension.

A microscopic study of a dilute coal-water suspension [23] in the presence of an electric field revealed the formation of coal particle chains and interlinked particle-particle structures. Figure 7 shows the effects of a uniform electric field strength (12 V/mm) at time lapses of 0, 60 and 240 seconds. Due to the relatively large mean particle size and ambient operating temperatures, thermal effects such as Brownian motion are considered to be negligible. In addition to the induced dipole interactions shown in Figures 6 and 7 there are repulsive electrostatic and steric interactions as well as the Van der Waals forces which are attractive in nature.
The particle strand formation shown in Figure 7 is attributed to the presence of these polarisation forces. Other electric field related particle interactions include a rotational particle torque associated with the dipole-field alignment and in the case of a non-uniform electric field, dielectrophoretic forces. Viscous forces resulting from shear fields such as those typically generated during suspension flow also act upon the particles.
Electrochemical dissociation of water molecules produces oxygen and hydrogen at the anode and cathode surfaces respectively, and was observed in the microscopic study as minute spherical bubbles (see Figure 7). The electrochemical production of a gaseous phase in the pipe flow situation would further complicate the enhanced flow conditions by introducing a solid-liquid-gas or multiphase region within the flow.

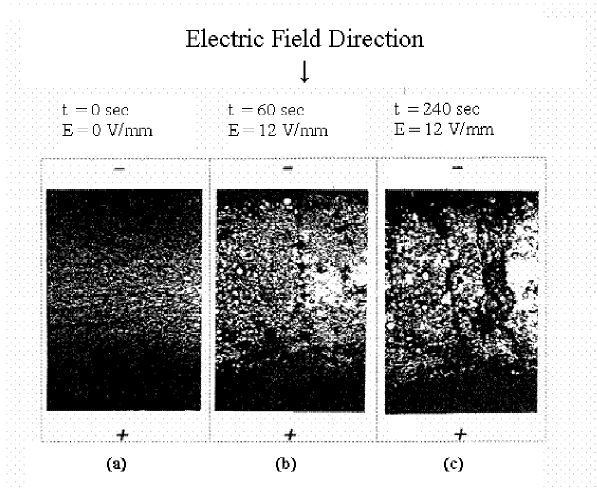

Figure 7. A microscopic study showing electrokinetically induced particle interactions for a dilute coal-water suspension. Source: [23,31].

Visual observations made at the pipe exit reveals that the coal-water suspension undergoes a degree of phase separation as a direct result of the electrokinetically induced change in concentration profile. A thin layer or film of low solids concentration envelopes a dense core region. The presence of a multiphase region at the pipe wall is supported by observations of crater-like indentations on the surface of the dense-phase core exiting the pipe. It is highly probable that these indentations are due to the production of hydrogen gas at the cathodic pipe wall.
The apparent solidity of the dense-phase region that forms when the electric field is applied is due to a combination of factors. Firstly, a relatively small increase in solids concentration within this region will produce significant changes in to the rheological properties of the suspension. For example, the yield stress of a concentrated coal–water suspension varies exponentially with the volume fraction of solids. Secondly, the interaction between coal particles is enhanced when an electric field is present. The particle dipole effects described earlier enable the formation of relatively large and ordered particle structures which contribute to the apparent solidity of the dense-phase regions within the flow.
At high solids concentrations coal-water suspensions normally exhibit shear thinning flow behaviour [23,28]. This phenomenon is less apparent at lower solids concentrations where the mean inter-particle distance is greater causing a reduction in the degree of interaction between particles. Numerous types of solid-liquid suspensions exhibit pseudoplastic flow behaviour which is primarily attributed to the extent of interaction between particles and the formation of particle conglomerates. Although it is common to characterise fluids that possess a yield stress by imposing a Bingham plastic model, a yield-pseudoplastic model

is better suited to suspensions that also exhibit shear thinning behaviour. The pseudoplastic flow behaviour of coal-water suspensions is described mathematically by a three parameter power law relationship which is normally referred to as the Herschel Bulkley Fluid model.

For coal-water suspensions at a solids concentration of approximately 30% (v/v) or greater, the measurement of a yield stress value becomes important in characterising the fluid flow behaviour [23]. There is a steep increase in the yield stress measurement at solids concentrations above 40% (v/v). This observation further supports the dependency of yield stress on particle interactions that are directly enhanced by the reduction in the mean distance between the particles. The presence of a yield stress in concentrated coal-water suspensions that are flowing in a circular pipe will create a region of zero-shear at the centre of the pipe.

The Zeta Potential of Coal Particles

A simple micro electrophoresis apparatus was used to determine the zeta potential of the coal particles at various pH levels and under conditions of dilute concentration. The measurements were made using an electrophoresis cell, a regulated voltage supply and a microscope. An electrical potential is applied across the two electrodes which are spaced at a specified distance from each other. The time taken for a coal particle to navigate across one graticule spacing is recorded for a specific electric field strength. The Smoluchowski equation [32] is applicable in determining the zeta potential of the coal particles. The natural pH of a prepared coal-water suspension used in this experimental trial is slightly acidic at pH levels of approximately 6.7. The zeta potential of the coal particles in this case is approximately -37 mV.

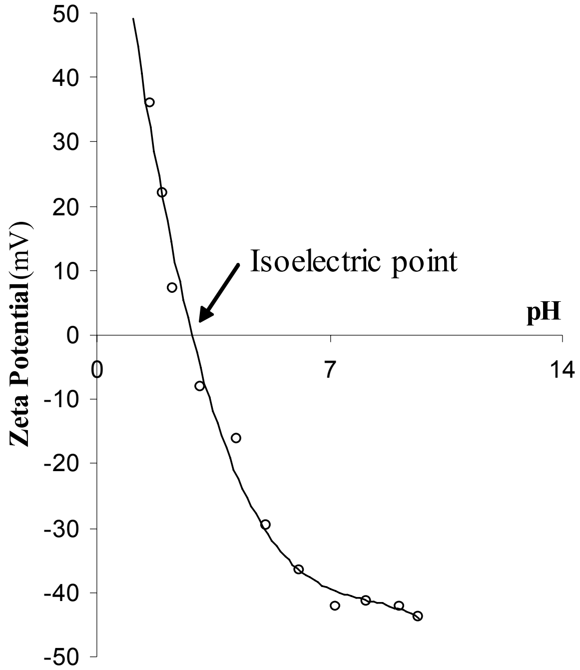

Figure 8. The variation of the zeta potential of coal particles at different pH levels.

The effect of pH on the zeta potential is shown in Figure 8. An important feature of this graph is that at a specific pH level the zeta potential is zero. This particle surface characteristic is referred to the isoelectric point. For this particular sample of coal the zeta potential is zero at a pH of approximately 2.8. Several experimental runs were carried out with the suspension pH adjusted to a level close to the isoelectric point and minimal flow enhancement was measured under these conditions. This result provides strong evidence that the magnitude of the zeta potential of the coal particles in suspension is an important driving force in electrokinetically enhanced pipe flow techniques.

Energy Efficiency and Practical Feasability

Although the economic advantages of slurry pipeline transportation improve as the throughput capacity and the distance is increased, the pumping power requirements may contribute to as much as 30 % of the total ongoing running cost of the pipeline system [11]. As mentioned earlier the electrical power consumption in small diameter pipes may be as high as an order of magnitude or greater than the actual reduction in pumping energy. The economic viability of intermittently spacing electrokinetically enhanced flow stages along the length of the pipeline may be further improved by the addition of solar powered cells or other renewable power sources.

Implementing these modifications to existing pipeline systems may be seen as a means of reducing transportation time or increasing the throughput capacity of the pipeline without altering the major aspects of the pipeline infrastructure such as the pipe diameter or the location of the pumping stations. Alternatively, the total number of pumping stations may be reduced or operated on a rotating basis which will not only increase the life span of the pumps but provide a certain number of pumping stations that can serve as stand-by units during normal pipeline operation.

An added benefit of embedding the electrodes within the wall of the pipe is the ease of manufacture of the inner sleeves which can be designed to fit into a standard pipe that is not necessarily composed of metal. Intermittently spaced pipe sections can then be used in pipelines constructed of composite materials such as concrete or materials that are non-conductive (plastic etc).

The use of non-aqueous mixtures and model fluids such as a silica based suspensions in electrokinetic experiments may also be useful in producing accurate and reproducible rheological data. In these instances, the particle characteristics such as size distribution and shape are far more readily controlled and therefore specific assumptions concerning the fluid and particle properties can be made.

As discussed in the previous section the zeta potential of the coal particles play an important role in the effectiveness of electrophoretic techniques. The particle zeta potential can be optimised by adjusting the pH level of the coal-water suspension. Increasing the pH level or alkalinity of the coal-water suspension would also significantly reduce the apparent viscosity which would effectively enable a higher solids loading to be used [23]. In addition, the electrical conductivity of the coal-water suspension would increase as the concentration of free ions increases and therefore a reduction in the resistance to the applied electric field should occur. Further analytical work on particle surface and suspension characteristics and their effects on the rheological properties and electric field intensity is required.

Prior to this study the anode-cathode geometries examined have necessitated a *flow-intrusive* positioning of the anodes within the cross sectional flow area. When analysing the economic benefits of electrokinetic flow enhancement in these anode-cathode systems, the actual reduction in pumping energy requirements should also be considered with respect to the normal flow in a pipe where the anodes are not present. The increase in frictional effects associated with these *flow-intrusive* systems can be emphasised by comparing the flow characteristics in circular pipe with a concentric annulus. In this comparison the flow conditions will be restricted to the laminar flow region and the fluid properties of the Newtonian test fluid are used (98% glycerol).

A general relationship between the pressure gradient and the mean velocity through a pipe of circular cross-section is given by the classical Poiseulle flow equation. If we assume that the fluid properties are independent of time and that Newtonian flow behaviour is applicable, this general relationship may be simplified to,

$$\mu_{\mathrm{glycerol}} = \frac{\tau_{\mathrm{wall}}}{\gamma} = \frac{\frac{(\text{-dP / dL})D}{4}}{\left(\frac{8V}{D}\right)} \tag{1}$$

Similarly, the flow of a Newtonian fluid in a concentric annulus that was described by Bird et. al., [3] results in the following expressions for the wall shear stress

$$\tau_{\mathrm{w}} = \frac{(-\mathrm{dP / dL})D}{4}\left[1-\left(\frac{1-\kappa^2}{2\ln\left(\frac{1}{\kappa}\right)}\right)\right] \tag{2}$$

and the mean axial velocity,

$$\mathrm{v_m} = \frac{(-\mathrm{dP / dL})\,D^2}{32\,\mu_{\mathrm{glycerol}}}\left[\frac{1-\kappa^4}{1-\kappa^2} - \frac{1-\kappa^2}{\ln\left(\frac{1}{\kappa}\right)}\right] \tag{3}$$

where 'κ' refers to the aspect ratio of the annulus (ie κ=d/D).
The pumping energy (E) is the product of the pressure gradient and the volumetric flow rate through the system and so the above equations can be further simplified and represented as,

$$E_{\mathrm{pipe}} = 8\pi\mu V^2 \tag{4}$$

and,

$$E_{\mathrm{annulus}} = \frac{8\pi\mu V^2\left(1-\kappa^2\right)}{\left[\frac{1-\kappa^4}{1-\kappa^2} - \frac{1-\kappa^2}{\ln(1/\kappa)}\right]} \tag{5}$$

Figure 9 shows the predicted pumping energy for a circular pipe and a concentric annulus with an aspect ratio of 0.1 using equations (4) and (5) respectively. For this value of the annular aspect ratio, there is a pumping energy increase of approximately 72% compared to the circular pipe system. For low values of the annular aspect ratio the discrepancy in the corresponding volumetric flow rates is negligible and so the mean axial velocity is used in Figure 9. An important conclusion made from this comparison is that by simply using a non-intrusive anode-cathode geometry embedded within the pipe wall, an immediate and significant reduction in the pumping energy requirements can be achieved. Figure 9 also shows the reduction in pumping energy for a coal-water suspension flowing in a helical anode-cathode geometry when a high electric field is applied.
Combining equations (4) and (5) on a volumetric basis gives the following dimensionless pumping energy ratio,

$$\frac{E_{\mathrm{pipe}}}{E_{\mathrm{annulus}}} = \left[\frac{1-\kappa^4}{1-\kappa^2} - \frac{1-\kappa^2}{\ln(1/\kappa)}\right]\left(1-\kappa^2\right) \tag{6}$$

As is seen from equation (6) this energy ratio is dependent on the aspect ratio of the annulus, or more simply the diameter of the central anode at a specific pipe diameter. Figure 10 shows that even an extremely narrow central anode can significantly effect the pumping energy requirements. A central anode that is two orders of magnitude smaller than the pipe diameter increases the pumping energy by almost 30% whilst the pumping energy is doubled at an aspect ratio of approximately 0.15. The positioning of an anode at the central axis of a circular pipe also maximises the frictional forces due to the fact that the velocity is a maximum at the pipe axis. Also, the anode-cathode gap is maximised in a concentric annulus which effectively increases the electrical resistance of the system. There are significant advantages and incentives in using non-intrusive anode-cathode geometries, both in construction and installation as well as energy efficiency.

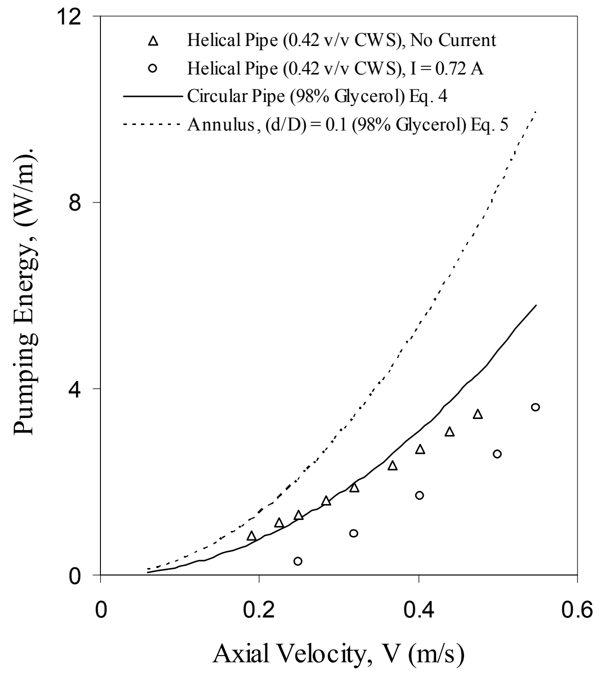

Figure 9. The predicted variation in pumping energy with mean axial velocity for Newtonian Laminar flow (Equations 4 and 5) and a 0.42 v/v CWS flowing through a helical anode-cathode pipe geometry.

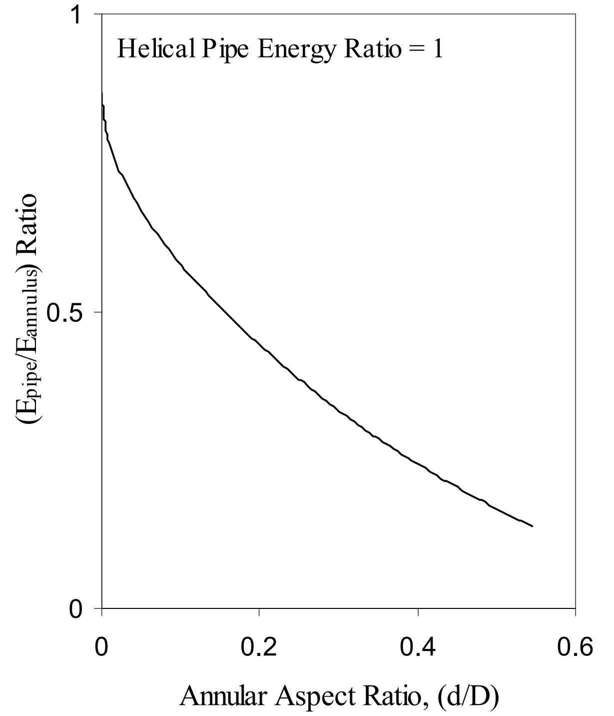

Figure 10. The effect of the annular aspect ratio on the predicted pumping energy ratio for a concentric and annular geometry.

The high electrical energy consumption for this pipe flow enhancement technique economically prohibits its use along the entire length of the relatively small pipe diameter used in this study. Currently, work is being carried out that will ascertain the degree of flow stability, electrical resistance and film formation efficiency at higher pipe diameters and pipe lengths. This work will assist in assessing the economic feasibility of using electric fields to enhance the flow and continuously separate dense solid-liquid suspensions in pipes.

Conclusions

It has been experimentally demonstrated that the application of electrokinetic techniques in the continuous flow of concentrated black coal-water suspensions in a non-intrusive helical anode-cathode geometry effectively causes a significant reduction in the wall shear stress. This reduction in frictional force at the pipe wall surface is attributed to a decrease in the mean concentration of coal particles in this flow region caused by the migration of negatively charged coal particles towards the anodic surface. Experimental measurements using a modified tube rheometer show that a reduction in the specific pumping energy requirements of approximately 80% is possible. For the small pipe diameter used in this study the electrical energy requirements are economically unfavourable if used along the entire length of slurry pipeline system. Further experimental work at higher electric field strengths and greater pipe diameters is required as well as an investigation into the stability of the electrokinetically enhanced flow conditions. In addition, analytical work is required focussing on areas such as design optimisation, pipe wall slip correction, suspension behaviour at higher electric field intensities and fluid flow modelling.

Acknowledgments

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